Chapter 3 Spatial Knowledge

This dissertation research is the first study of its kind on wayfinding within the context of virtual worlds. However, wayfinding in general is certainly not a new research topic. From William James as early as 1890 (James, 1890) to the present, psychologists have been interested in the human conception of space; how it is perceived, how it is cognitively organized, and how it is recalled. This chapter will survey the experimental psychology literature on issues related to wayfinding. We are particularly concerned with the following questions:

- What is spatial ability?
- What is spatial knowledge?
- How is spatial knowledge represented?
- How is spatial knowledge acquired?
- How is spatial knowledge accessed?

Answers to these questions will provide a psychological foundation for the design principles to follow. It is these principles which require validation in the virtual world domain. We will find in the next chapter that in many ways, practical application of these principles has relied on a few basic generalizations of physical space. Virtual worlds, however, tend to break the rules of physical reality thus opening questions as to the validity and extensibility of psychological principles of human spatial orientation and wayfinding. This chapter and the next serve to present the related background and supporting knowledge on which this dissertation is built.

Spatial Ability

According to developmental psychologist Jean Piaget (Piaget & Inhelder, 1967), children go through four distinct stages of formal operations of cognitive development. These stages are best described by the frame of reference the child uses to locate and orient objects within the environment (See Table 3-1).

Operational Development	Frame of Reference	Spatial Relations
Sensorimotor	n/a	n/a
Preoperational	Egocentric	Proximity Separation Open/Close Between Order
Concrete Operational	Fixed	Enclosure Continuity Geometry
Formal Operations	Coordinate	Proportional Scale Reduction Distance Estimates Coordinates

Table 3-1 The developmental stages of formal operations and spatial ability.

The *sensorimotor* stage (birth–2 years) is characterized by the child's ability to experience the world only through the senses. A child in this stage is limited in both its motor and cognitive capabilities making wayfinding and object orientation a non-issue.

In the *preoperational* stage (2–6 years), the child is only able to locate objects in the environment relative to the body. These children are characterized by their *egocentric* frame of reference in which objects are recognized only from familiar perspectives. A house viewed from its front will not be recognized when viewed from the side or the back.

A child in the *concrete operational* stage (7–9 years) develops a *fixed* coordinate system in which the body and other objects are oriented relative to static landmarks in the environment. A fixed coordinate system enables recognition from multiple perspectives but only within the constraints of the known coordinate system. This is illustrated by Figure 3-1 where the child can only recognize the way home when viewed within the fixed coordinate system based at the school.

Finally, in the *formal operations* stage (11 years), the child is able to orient to more abstract coordinate systems external to the body. Formal operational children orient in a *coordinate* frame of reference. In this case, abstract frames of reference are used such as the cardinal directions, polar coordinates, or latitude/longitude.

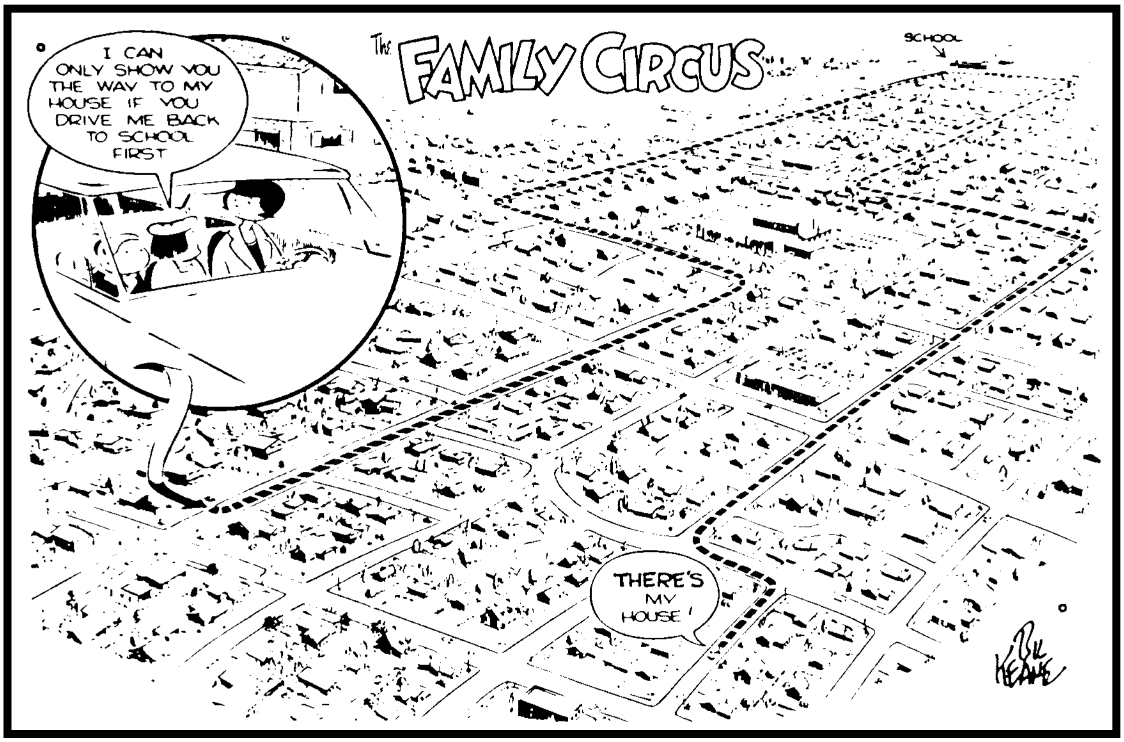

Figure 3-1 A fixed coordinate system.

Within these frames of reference emerges the ability to form spatial relations. Topological relations are the first to appear. Properties such as proximity, separation, open, close, between, order, enclosure, and continuity develop during the preoperational and early concrete operational stages. This is followed by projective relations such as straight lines and triangles which are invariant with changes in perspective. The last type of spatial relations to develop are Euclidean relations such as proportional scale, reduction, distance estimates, and coordinates. These abilities are often categorized in terms of two spatial factors; visualization and orientation (McGee, 1979). Visualization involves the ability to mentally manipulate a visual stimulus whereas orientation involves the comprehension of the arrangement of elements within a visual stimulus. (See Appendix A.) Both factors directly relate to higher level spatial tasks such as wayfinding (Thorndyke & Goldin, 1983).

Beyond an understanding of spatial ability, we need to know more about what spatial knowledge really is and how it is extracted from the environment, mentally organized, and retrieved for use in wayfinding tasks. This will help to describe a framework for providing environmental information for wayfinding.

Spatial Knowledge

Many typical activities in which people take part every day involve the performance of spatial tasks in large-scale environments. These tasks are based on spatial knowledge which is gathered from the environment itself. Spatial knowledge includes perceptual information (e.g. What does a place look like? What does it sound like?) as well as information about distances and directions from place to place. It also includes inferred knowledge about places unseen and paths untraveled (e.g. Short-cuts). Thorndyke describes spatial knowledge in terms of three levels of information (Thorndyke & Goldin, 1983; Thorndyke & Hayes-Roth, 1982; Thorndyke & Stasz, 1980).

1. ***Landmark knowledge*** represents information about the visual details of specific locations in the environment. It is memory for salient perceptual features in the environment such as an architecturally unique building that dominates the skyline. He refers to this information as *perceptual icons* or *images*. This type of information is acquired by directly viewing objects in an environment or by viewing indirect representations such as photographs. Location recognition is accomplished through landmark knowledge. Presumably, an image of the current scene is matched against known or previously viewed scenes.
2. ***Procedural knowledge*** (also called route knowledge) represents information about the sequence of actions required to follow a particular route. This has four components:
   - A sequence of actions which constitutes a route description
   - A series of perceptual features encountered along the route
   - Distances between locations experienced as sensations of motion, speed, and time

- Angles or bearing changes at turning points along the route

In other words, procedural knowledge connects isolated bits of landmark knowledge into a larger, more complex structure. This type of knowledge is acquired either through direct experience or through simulated experience such as video (Goldin & Thorndyke, 1982). Both landmark and procedural knowledge are defined in terms of an egocentric frame of reference.

3. ***Survey knowledge*** represents configural or topological information. Object locations and inter-object distances are encoded in terms of a geocentric, fixed, frame of reference. Survey knowledge is map-like in nature. Accordingly, it can be acquired directly from map use. However, there are complications with this method dealing with inflexibility of the corresponding representation. (See Knowledge Acquisition on page 33.) Prolonged exposure to navigating an environment directly also leads to survey knowledge.

These types of spatial knowledge are *not* mutually exclusive. Each level of knowledge builds on previous levels of knowledge. Landmark knowledge is strictly static information. An example will serve to illustrate the distinctions between each type of knowledge (See Figure 3-2).

> After viewing photographs of a friend's vacation to Washington, D.C. (assuming you have never been there), you have a form of landmark knowledge about the White House, the Washington Monument, and the U.S. Capitol. No information exists yet to link these together spatially since the photos showed each separately. Shortly thereafter, during a business trip to Washington, you walk around the downtown area. During your walk down Pennsylvania Avenue, you see the White House with the Capitol off in the distance. Crossing over to the Mall, you see the Washington Monument with the Capitol on one end of the green. Now that the landmarks have been linked together, procedural knowledge is formed. Landmarks can be identified and paths between them can be determined. However, your brief experience with Washington has not given you a complete image. Only relative information exists with respect to the three landmarks. Later, on the flight home, you look down on the city and identify each of the landmarks previously visited. An absolute coordinate frame of reference has now been defined on which the relative information previously attained can be founded along with new information about other sites only viewed from the air. Although your

knowledge of Washington is still immature and not very useful for performing complex wayfinding tasks, it has a structure exhibiting all three levels of spatial knowledge.

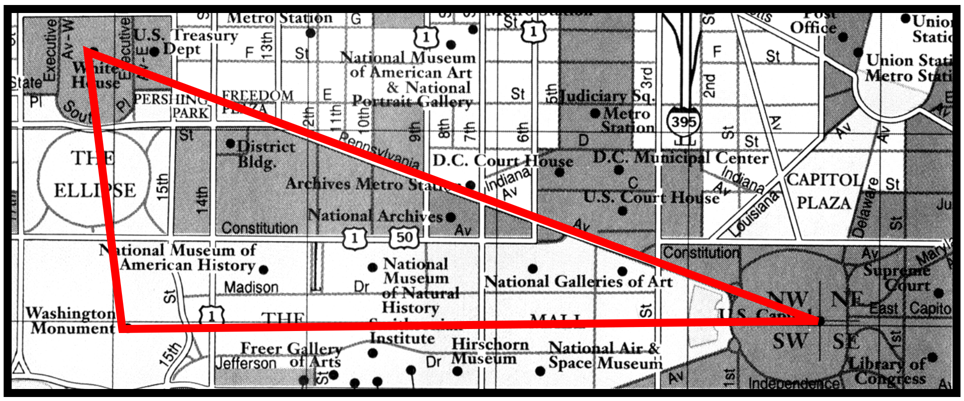

Figure 3-2 The Federal district of Washington, D.C.

This three-level description of spatial knowledge will be referred to extensively in the next section involving cognitive map theory. In particular, it fits directly into what is known about spatial knowledge acquisition. Issues relating to spatial knowledge representation will involve the structure of survey knowledge and how it is developed from procedural knowledge. However, before we address those issues, we will first discuss the notion of innate orientation ability. Can animals or humans orient themselves in the absence of perceivable cues?

A fundamental question associated with orientation is whether it is innate or determined from external cues. There are many stories of lost dogs traveling hundreds of miles to return to their home. Unfortunately, what isn't documented are the vastly larger number of stories of lost dogs that stay lost. Through homing experiments, animals such as dogs and horses seem to show an ability to memorize routes but have not been shown to sense direction effectively. Similar experiments on many small mammals and birds, on the other hand, have shown their ability to locate familiar territory far more often than a random searching theory would allow indicating an innate sense of direction.

This question, when applied to humans, is a hotly debated issue. Lockley (1967) and Passini (1984) provide extensive evidence to the effect that humans have no innate ability to sense direction. When useful cues are not available, humans easily become disoriented. Even relatively primitive cultures such as the Lapps and the Eskimos exhibit this lack of direction finding. To these cultures, orientation is essential because of the frozen, featureless environment in which they live. However, they have been shown to be no more adept at this task than the average modern city dweller. They simply make better use of the few cues provided them. This is further supported by Morris (1981) who showed that rats are able to locate a target even though it cannot be seen, smelled, or heard provided relative positional cues (e.g. direction, distance) are present allowing an organized search to take place. Subsequent searches for the target use the same relative cues causing the rat to exhibit behavior which could easily be mistaken as supportive of innate direction finding ability. Again, the adaptive nature of the animal makes efficient use of what information is present.

On the other hand, Walmsley and Epps (1988) present evidence to the contrary. They expanded on research done by Baker (1981) who suggests that humans do in fact have an innate sense of direction which is based on the Earth's magnetic field. Baker showed that subjects wearing magnets while performing orientation tasks were outperformed by subjects not wearing magnets. Walmsley performed an experiment involving moving blindfolded subjects to remote locations and observing their ability to recall the path taken or the direction to home. In summary, results showed support for the following:

1. The sense of direction is innate. It is evident in both the southern and northern hemispheres.
2. The sense of direction is observable at an intra-urban scale. It is not necessary to travel very large or very short distances to observe the phenomenon.
3. The sense of direction is not a learned skill. Children are as proficient as adults.

Interestingly, subjects showed an unwillingness to trust their sense of direction since it is not traditionally used exclusively. But as they became more and more disoriented, they found no viable alternative and grew to depend on it. However, even Walmsley admits that magnetism is probably only useful in giving the starting position or direction for a journey and even then, it is only useful in the absence of maps and environmental cues such as topography, the sun, wind direction, or man-made signs. For this reason, we will assume that no innate human orientation ability exists. Even if such a phenomenon does exist, its effects on the problems of wayfinding are minimal and its use in virtual environments would be limited to worlds aligned to the real world.

Cognitive Map Theory

Psychologists have long been interested in the ways in which people mentally manage space. The term “cognitive map”[†] has been used to describe the process of formulating and maintaining spatial knowledge. Research in this area has focussed on knowledge representation and organization, knowledge acquisition, and knowledge accessibility on task demands. This section will survey the literature on cognitive map theory as it applies to wayfinding. Our goal is to understand the cognitive processes and resources associated with wayfinding in order to develop a scientific foundation for the design principles to follow.

Although the importance of mental representations of space have been discussed as early as 1913 (Towbridge, 1913), it was not until Tolman began to investigate cognitive maps (Tolman, 1948) that it became a primary research issue. Tolman performed a number of experiments with rats to find if their behavior supported the stimulus-response model held by the behaviorists of the day[‡] or if a more complex mental phenomenon existed. Tolman showed that rats did in fact learn spatial locations from their environment dispelling the view that their actions were simple stimulus-response connections. To illustrate this point, one experiment had rats trained to find the food box (G) (See Figure 3-3). After a training period, the rats were moved to the “sunburst” maze. If their behavior was a simple stimulus-response connection, the rats would investigate the blocked path. The data

† Also “mental map”.

‡ The behaviorists believed that all mental processes could be studied in terms of behavior. This was the dominant theoretical perspective of Tolman’s era. Tolman was a part of a broader movement toward cognitive theory which takes an information processing perspective.

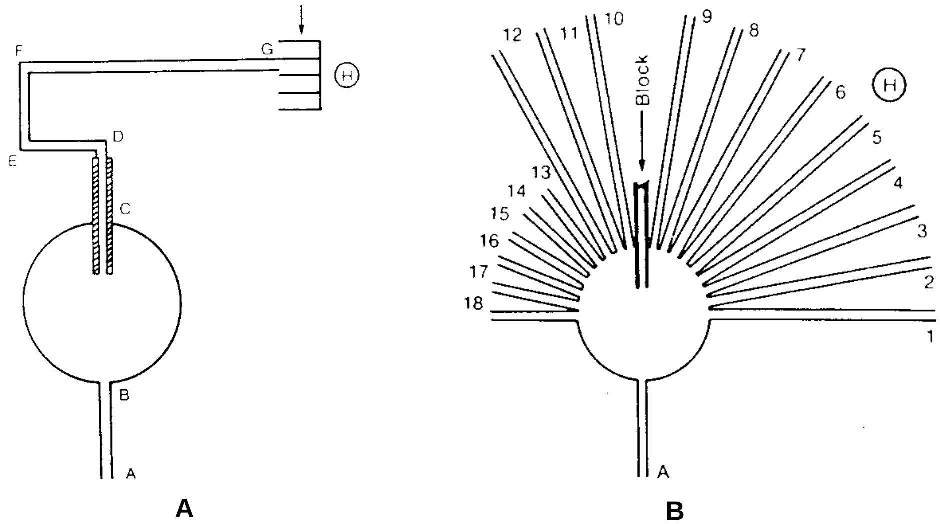

Figure 3-3 **A**. Tolman's training maze. **B**. Tolman's "sunburst" maze. Reproduced from Tolman (1948).

clearly showed that the rats headed directly to the food (path 6) showing that they had inferred the direction from the previous trials. Although this early work showed that learning had taken place, it did little to explain what knowledge had been acquired or how it was represented.

Knowledge Representation

Studies on spatial distortion have shed some light on mental representations of space. Models can be constructed to explain consistent errors in distance or direction estimation. From these models, in order to develop autonomous wayfinding, the robotics community has developed a number of computational models which can exhibit simple forms of spatial abilities.

A model of spatial knowledge acquisition and representation must account for (Golledge, Smith, Pellegrino, Doherty, & Marshall, 1985):

1. Different types of knowledge and forms of representation
2. Systematic inaccuracies and distortions in the cognitive representation
3. Behavioral errors associated with inaccurate and hierarchically organized knowledge

4. Acquisition and representation based on episodic experience and subsequent generalization. (i.e. How does landmark and procedural knowledge become survey knowledge?)

As illustrated in this list, spatial knowledge representation, acquisition, and accessibility are tightly coupled. The process by which spatial knowledge is acquired directly affects the representation it takes. Furthermore, spatial knowledge representation directly affects the ability to access the information. This section will make generalizations about knowledge structure leading to a more specific discussion in the next section when methods of knowledge acquisition are considered.

Stevens and Coupe (1978) present evidence through their experiments supporting the notion of a hierarchical representation of geographical information. They showed that larger, containing geographic regions can distort people's judgement of direction. For example, residents of San Diego were asked to indicate the compass direction to Reno, Nevada. The data shows that most subjects chose a north-northeasterly direction (See Figure 3-4.). Actually, Reno is north-northwesterly from San Diego. The data also shows that this phenomenon applies in general across the country. What this tells us is that the actual positions of Reno and San Diego are not encoded directly. Rather, the generalization that Nevada lies north-northeasterly from California alters judgement indicating that the response is inferred. The point here is that it is not practical to store all possible spatial relationships. Therefore, only a few relations are made with other relations being made within each higher grouping in a hierarchical fashion.

This hypothesis is further supported by Howard and Kerst (1981). In this study, students grouped portions of the campus into larger parts in order to mentally organize a large number of buildings. The hierarchical structure of the representation was exhibited by the students' tendency to cluster groups of buildings which were not actually grouped together spatially thus distorting the cognitive map.

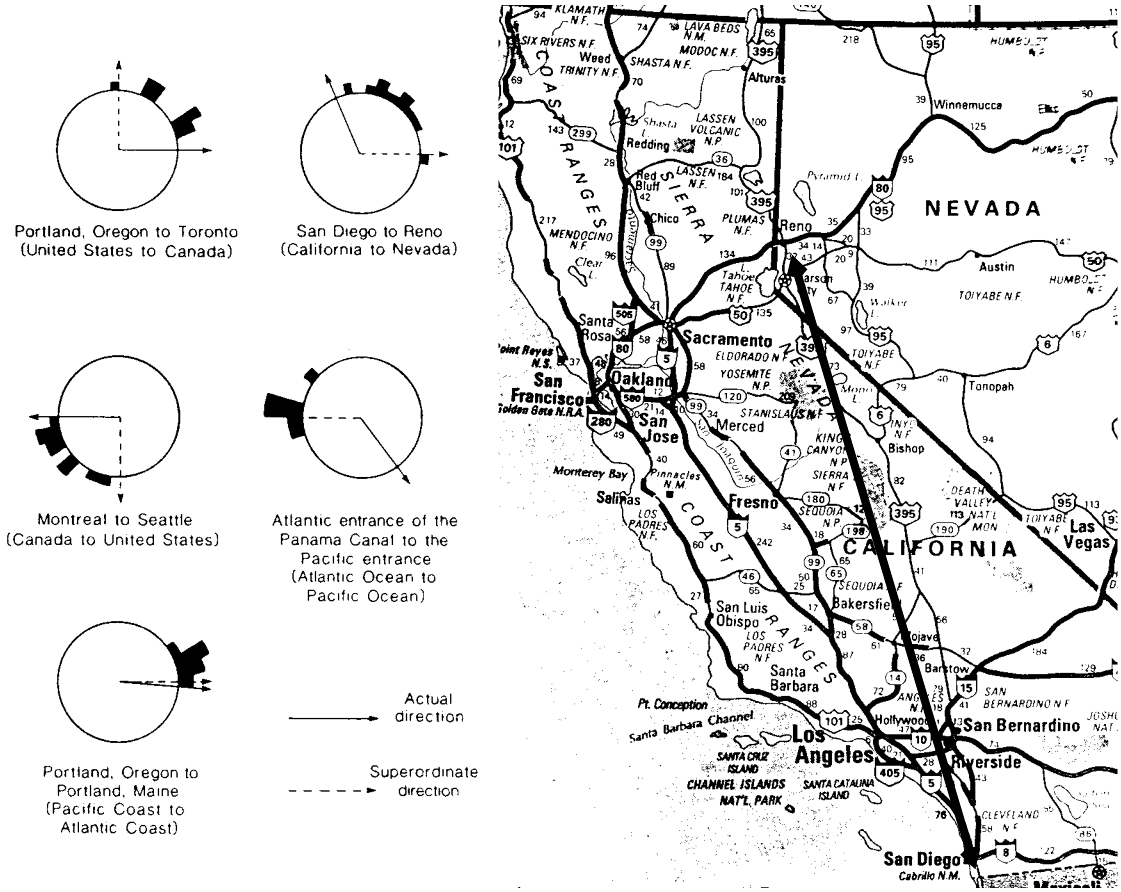

Figure 3-4 Distortions in judgement of direction of cities. Subjects indicated the direction from one city to another by drawing a line from the center of the circle to the edge. The histogram shows the frequency that subjects selected a given direction. Also shown is the true direction and the superordinate direction. Note the bias toward the superordinate direction. Reproduced from Stevens and Coupe (1978). Also shown is an actual map of San Diego and Reno to show the extent of the distortion.

Canter and Tagg (1975) investigated the effects of familiarity on distance estimation. The conclusion drawn was that familiarity leads to underestimation of actual distance. Furthermore, Holahan (1982) discusses the role of life-style and social involvement in addition to familiarity in the development of cognitive maps. Life-style and social involvement directly affect the types of places a person is likely to frequent in an environment. These places and those in close proximity will be densely represented while other places will not. The overall effect on the topological representation will be a distortion of shape and relative distances due to the variability of familiarity.

This is supported and further clarified by Chase (1983) who reports a variety of errors in spatial judgement found in taxi drivers. Based on our definition of spatial knowledge, (See Spatial Knowledge on page 22.) procedural knowledge will evolve into survey knowledge with extensive exposure to an environment. Therefore, one would conclude that taxi drivers would have highly developed survey knowledge as a result of their extensive route following. However, the study found that experienced taxi drivers in Pittsburgh had no better representation of the environment than novices. They did excel in route finding but their overall survey knowledge was poor. For example, trapezoidal city blocks were consistently drawn on paper as rectangles. This is further illustrated by their tendency to infer direction of neighborhoods from their route knowledge rather than obtain it directly from survey knowledge. The findings indicate that spatial information about the environment is not directly encoded but rather is built up relatively. Also, simplifications are often made to complex topological structures.

The developing child first notes landmarks in the environment (See also Knowledge Acquisition on page 33.) and later paths between them. This is consistent with Piaget's model of cognitive development and also with Thorndyke's model of spatial knowledge. Later in development, the child is able to cluster knowledge together and eventually form an overall framework (i.e. a hierarchy) (Holahan, 1982).

Theories of information processing can help us to understand the ways in which cognitive maps are formed and used. The *imagery* theory suggests a direct relationship between the mental representation and reality. The *propositional* theory suggests that spatial information is encoded in an abstract form allowing it to be stored in the same format as verbal information. However, it has also been proposed that both are correct and that information is stored abstractly but can be manipulated in a manner consistent with the imagery theory. Lloyd (1989) suggests that procedural knowledge is stored verbally while survey knowledge is stored as imagery. In any case, our point here is that the knowledge is built up from the general to the specific in a hierarchy and that this structure is exhibited in the types of spatial distortions displayed. A cognitive map may or may not be a “picture-in-the-head”, but we can say for certain that particular types of information are perceived and stored in memory and that they are accessed in a way consistent with the theory of hierarchical structure.

We have to be careful in discussing computational models of cognitive maps. The objective of a computational model is not necessarily to validate cognitive theory but rather to accomplish some goal; in this case, autonomous navigation and wayfinding. This is indicated by the simplicity of some models which take a more practical view of the problem and attempt to solve it pragmatically without regard for psychological validity. However, it is useful to discuss these models and the ways in which they have structured spatial information.

Baird and Wagner (1983) present one such simple model for spatial representations. The physical environment is first perceived. Judged distances between places result in distance pairs. As the environment is explored, an NxN matrix of distance pairs is filled in (N is the number of “places” in the environment.). These are chained together either randomly or directed by landmarks. This forms a two-dimensional map which Baird calls the cognitive map. This model suffers from several shortcomings. First, it is not a hierarchical representation. Topological information is not easily accessible. Most importantly, it requires a thorough exploration period before it becomes functional.

Kuipers (1978, 1983; Kuipers & Levitt, 1988) was the first to develop a computational model of a cognitive map adhering to Thorndyke’s spatial knowledge classification (Thorndyke & Stasz, 1980). The model contains separate representations for routes (procedural knowledge), relative-position information (survey knowledge inferred from procedural knowledge), and topological connections (survey knowledge). Kuipers defines a cognitive map as

> the body of knowledge of a large-scale environment that is acquired by integrating observations gathered over time, and is used to find routes and determine the relative positions of places.

Note that the concept of “place” must be present in order to build the map. Conceptually, the map is a graph with “places” as nodes and “paths” as edges. The model of spatial knowledge representation described falls into four levels: sensorimotor, procedural, topological, and metric (See Figure 3-5). The dynamics of the systems are described as a series of views and associated actions. Most importantly, Kuipers’ model is hierarchical with each level building upon lower levels. Although the model is comprehensive, it still lacks any representation of experience or ability to transfer wayfinding techniques from one space to another. However, this would seem to be much more of an issue with human wayfinding than robotic wayfinding.

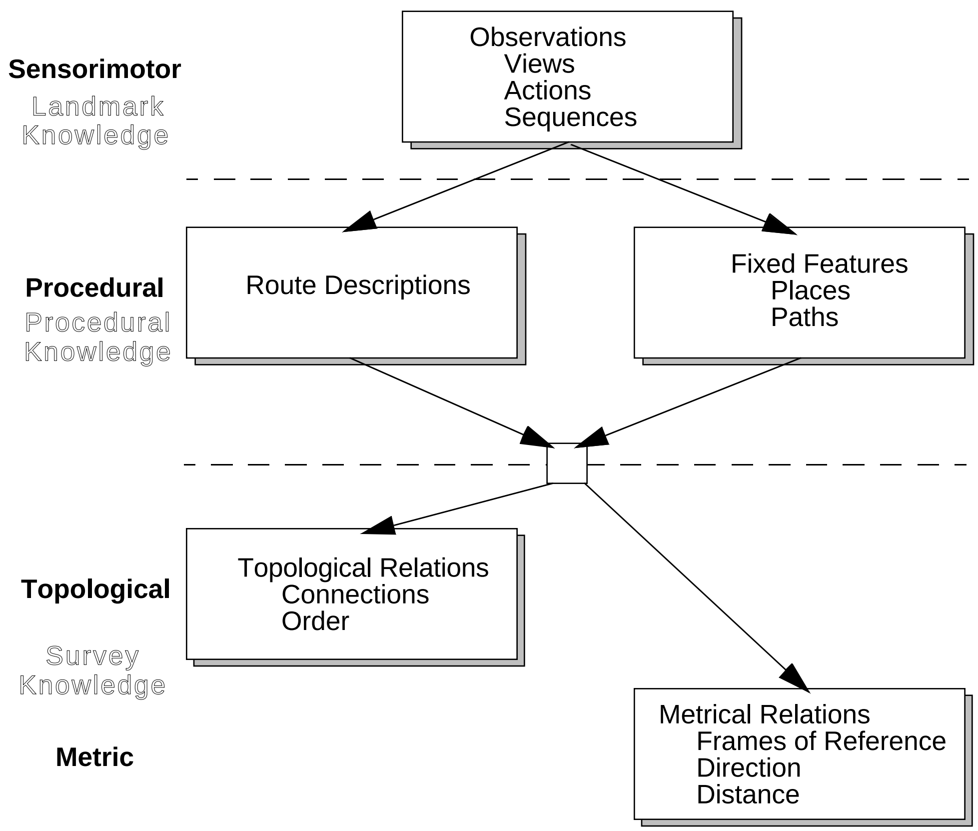

Figure 3-5 Kuiper’s cognitive map model. Arrows indicate representational dependencies. Note the indication of Thorndyke’s spatial knowledge types. Reproduced from Kuipers (1983).

Touretzky, Redish, and Wan (1993; Wan, Touretzky, & Redish, 1994) are focussing on understanding wayfinding at a neural level so that better robotic navigation algorithms can be developed. Touretzky identifies four representations of space suitable (some more than others) to robotic navigation algorithms.

1. *Topological*: A topological representation models the space as a collection of discrete places. It can be manipulated as a graph. This is called a narrow representation because it cannot account for paths not in the model (no corner cutting).
2. *Metric*: A metric representation models the space in polar or Cartesian coordinates (spherical or Euclidean space).
3. *Occupancy grids*: Occupancy grids are a mix of the previous two methods. The space is diced up into two-dimensional cells. It can be thought of as discrete places but they are all contiguous.
4. *Cognitive maps*: As defined by Kuipers, cognitive maps contain place knowledge, metrical information, topological information, and route knowledge.

Topological representations do not recognize unexplored space and so are unable to infer routes through it. Metric representations model the whole space but are unable to recognize "places" within it. An occupancy grid tries to merge the two previous methods but still suffers from being unable to infer paths over unexplored terrain. The grid is a type of place holder. Objects and places in the space are not given as a priori knowledge.

Touretzky makes a distinction between landmarks and reference points. Landmarks are distal cues which provide primarily distance and bearing information while reference points are internally-based (subjective) and need not have any sensory attributes. An example of a reference point might be a start location.

Knowledge Acquisition

Tolman's experiments showed that wayfinding was more than a simple stimulus-response mechanism. There was some form of learning taking place. But what was being learned? This section will address issues of spatial learning. What information is acquired from the environment? How is it organized into a unified structure? How does the type of learning or the form of the stimulus affect what is learned or the structure of the information?

Golledge, Gale, Pellegrino, and Doherty (1992) contend that there are no definable procedures in acquiring spatial knowledge. Tracing a route between origin and destination not only does not necessarily require the integration of spatial layout but often doesn't use the information at all. Thus the development of configurational knowledge structures is not a simple consequence of learning declarative (i.e. objects, features, facts) and procedural knowledge.

On this same issue, Herman, Chatman, and Roth (1983a) report that sighted subjects infer spatial locations in an unfamiliar large-scale environment better than congenitally blind subjects indicating the importance of visual imagery. This is further indicated by blindfolded subjects outperforming congenitally blind subjects on some tasks. Klatzky, Loomis, Golledge, Cicinelli, Doherty, and Pellegrino (1990) expand on this by noting that it is easier to retrace known routes than to infer new ones without sight. This is dependent on route knowledge. Survey knowledge is necessary for short-cuts since it requires an overall view of the environment. Thus the study seems to point out a missing connection between route and survey knowledge when vision is disabled. These issues will be revisited later in this section when we look at specific instances of spatial learning.

Rieser (1983) states that two processes are involved with spatial orientation; *cognitive processes* which are deliberate in nature and *perceptual processes* which are automatic. This is the case for many high level tasks. However, as a wayfinder becomes more familiar with a space, the task as a whole may become more automatic. Consider the case of driving to work in the morning. Very little conscious effort goes into the task. But if a road is closed, the driver must deliberately determine a new path.

According to Reiser, wayfinding involves two capacities; maintenance of orientation and extraction of spatial layout. In other words, the wayfinder must be able to extract useful environmental information and organize it spatially requiring that accurate orientation be maintained at all times. This is further supported by Sadalla and Staplin (1980) stating that spatial knowledge is developed as a cognitive reconstruction of operations and perceptual elements involved in traversing a space.

Cognitive maps and spatial inference abilities go hand-in-hand. Good cognitive maps may be the result of superior spatial inference abilities, and vice versa. The two capacities mentioned above are the vehicles by which spatial knowledge is acquired resulting in cognitive maps and spatial inference abilities.

In *Cognition and Reality*, Neisser (1976) deals with three major topics related to this thesis: perception, schemata, and cognitive maps. Perception is concerned with how information from the world is input into the information processing pipeline (assuming that such a pipeline exists). Neisser suggests that structures he calls *schemata* direct perception. That is, they anticipate and organize information into a useful construct. This is a precursor to imaging. Cognitive maps (called orientation schema) are a form of imaging. The basic rule-of-thumb concerning perception and cognition is that information processing in its entirety is a relative process. Which stimuli we attend to is dependent on context. The actions we take based on the further processing of those stimuli are also based on context. This is different from the theory that a cognitive map is like a “picture in the head”. In fact, Neisser’s view of cognitive maps is that of a process rather than that of a resource.

Sholl (1987) expands on Neisser’s theory by making a distinction between primary and secondary spatial knowledge in an effort to identify the effect of knowledge sources on imaging ability. Primary knowledge is acquired directly through experience navigating the world or through viewing the world. Secondary knowledge is acquired typically through maps or a model of the world. Secondary knowledge has picture-like properties while primary knowledge does not. Secondary knowledge has a fixed, geocentric frame of reference while primary knowledge has a flexible, egocentric frame of reference. In other words, maps are encoded in the orientation in which they are viewed. Direct learning also has a preferred orientation but is flexible.

Sholl introduces a topic which we will delve into in some depth for the remainder of this section. Clearly, the distinction between primary and secondary knowledge must be made because not only are the sources of the knowledge different, but each has a different effect on the flexibility of the resulting knowledge structure. This issue will flesh out some important facts which we can use in designing the sources for primary (environmental) and secondary (map) knowledge. We will begin by studying issues associated with maps and map reading in general and conclude with a discussion of the use of maps along with other learning methods for acquiring spatial knowledge.

The art of cartography is thousands of years old. But through that time, the basic characteristics of maps have remained primarily unchanged. In map making, we are interested in four major decisions (Downs & Stea, 1977):

1. **Purpose:** What are we interested in representing?
2. **Perspective:** What viewpoint or perspective are we taking?
3. **Scale:** At what scale is the representation?
4. **Symbolization:** How do we construct the representation?

Basically, a map is an abstraction of physical space. The symbolization used is dependent on its purpose. For example, the symbols on an aviator's chart are different from those on a road map. Blades and Spencer (1987) note that most people are unable to plot a route based on a typical map. This may have to do with maps' symbolic nature or simply inexperience with the task. Simutis and Barsam (1983) discuss contour maps and the inability of soldiers to read them. Again, the symbolization scheme is at issue. However, in order to keep this discussion general, we will not concern ourselves with symbolization and map purpose issues but rather with the ability of the user to locate both himself (perspective) and other objects on the map and to relate that knowledge to the physical world (scale).

Landau (1986) showed that simple map use (not highly encoded) is possible with no training as long as the relationship is made between the map and the physical space. The analogy between maps and their corresponding physical space is thought to be a part of our natural spatial abilities. This is reinforced by the earlier work of Herman, Herman, and Chatman (1983b). The experiments described are supportive of the use of tactual maps for the blind. Subjects were able to haptically explore the spatial relationships between objects on a table. The scalar relationship between maps and physical space does seem to be an innate ability.

On the issue of perspective, Levine, Jankovic, and Palij (1982; Levine, Marchon, & Hanley, 1984) performed experiments altering the orientation of the map with respect to the world in order to determine the effect on an observer's ability to place himself on the map and to locate other places in the world. Results supported earlier studies showing that cognitive maps are the result of spatial learning, and that they have picture-like qualities. Levine draws three conclusions from these experiments which are the basis for map design theory (See Figure 3-6).

- The ***two-point theorem*** states that a map reader must be able to relate two points on the map to their corresponding two points in the environment.
- The ***alignment principle*** states that the map should be aligned with the terrain. A line between any two points in space should be parallel to the line between those two points on the map.
- The ***forward-up principle*** states that the upward direction on a map (assuming it is mounted perpendicular to the floor) must always show what is in front of the viewer.

Note that the primary issue in map design principles is that the map be congruent with the environment. Why is this? The next section will look at a number of experiments which will explain this phenomenon.

As stated earlier by Thorndyke, survey knowledge can be acquired directly from maps. That being the case, what are the differences in survey knowledge acquired from maps from that acquired by experience? A number of studies have been performed to investigate this question.

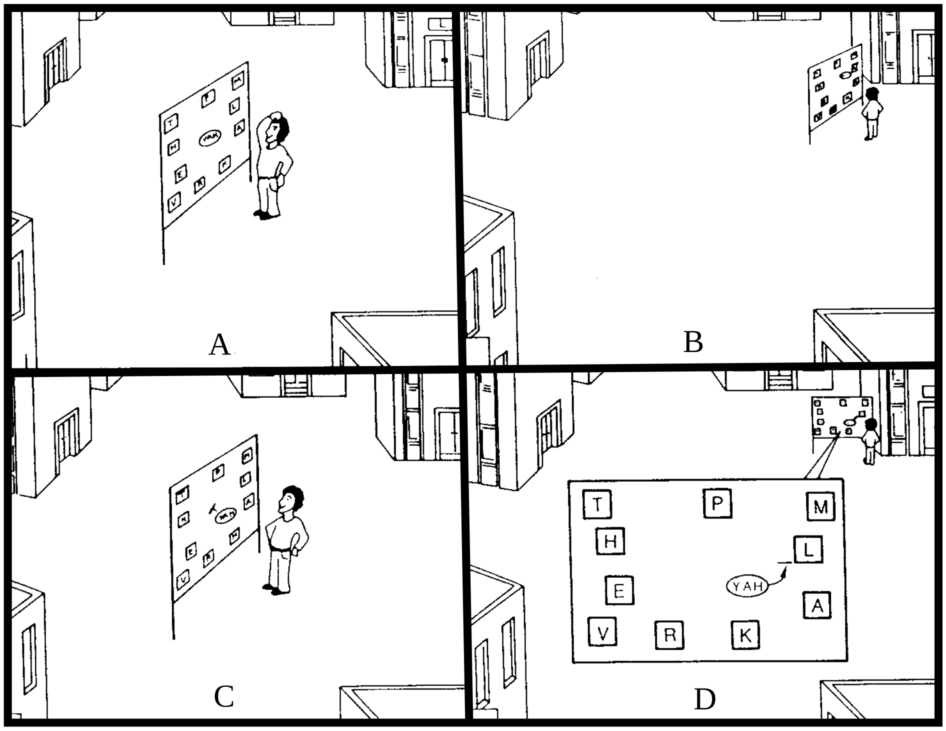

Figure 3-6 Guidelines for you-are-here maps. The most important principle is that the map be congruent with the environment. (a) In addition to the location of the viewer, at least one reference point is marked on the map. (b) The map is asymmetrically located near a prominent reference. (c) The YAH symbol incorporates two pieces of information: where you are on the map, and where the map is in the environment. This is indicated by an arrow on the map indicating view direction. (d) Redundancy: all the principles shown at once. Reproduced from Levine, et al. (1984).

From a map, people acquire survey knowledge encoding global spatial relations (Thorndyke & Hayes-Roth, 1982; Thorndyke & Stasz, 1980). This knowledge resides in memory much like a map. It can be measured and scanned. From navigation, people acquire procedural knowledge of the routes connecting diverse locations. Spatial judgements are performed by mental simulation of travel through the mental representation and mental algebra. As expected, in Thorndyke's experiments, map learners outperformed navigators on global tasks such as absolute distance estimation or short-cut determination.

However, navigators were better at landmark determination and route planning. As navigators gained experience, the superiority of map learners on global tasks diminished.

In a subsequent study (Goldin & Thorndyke, 1982), subjects were either taken on a bus tour of a previously unknown area or shown a film of a drive through the same area. Their spatial knowledge was supplemented by either a map of the area, an oral narrative of spatial relations, or nothing. They concluded that simulated navigation can be used as a substitute for actual navigation in some circumstances. A map supplement can improve survey knowledge previously acquired through navigation. However, Gale, Golledge, Pellegrino, and Doherty (1990) showed that although this may be true, actual field experience in spatial knowledge acquisition is better than a simulated form (such as videotape). Hirtle and Hudson (1991) studied two groups; one learned from maps and the other viewed a slide show (both are secondary sources). As expected, the map group excelled in survey knowledge acquisition while the slide show group had better procedural and landmark knowledge.

Evans and Pezdek (1980) showed in their experiments that flexible structures are learned from direct experience and orientation-specific structures are learned from maps. A subject who has learned only from a map[†] will have difficulties navigating the space from the north. The reason is that in facing south, the subject's cognitive representation[‡] is upside down. For every action, mental algebra must be performed to invert the map. However, this characteristic is not exhibited by subjects who learn a space from direct navigation. Their cognitive map is orientation-independent. This is the psychological foundation for Levine's map principles (See Knowledge Acquisition on page 33).

Expanding on the notion of flexibility of cognitive representation, Presson and Hazelrigg (1984) focussed on how cognitive representations are formed from the stimuli itself. A cognitive map was developed from one of three sources: from a map, walking blindfolded, or by viewing from a distance (as from a hilltop). When the area was learned indi-

† We will assume north is up on the map.

‡ Which has north up, like the map.

rectly (from a map), subjects performed best when they were aligned with their mental representation. These orientation effects were not present in other subjects. They conclude that secondary learning (i.e. indirect, map) results in a precise, fixed orientation representation while primary (i.e. direct) learning results in a less precise but flexible representation.

In a later experiment, Presson, DeLange, and Hazelrigg (1989) found that small displays (usually maps) tend to lead to orientation-specific representations while larger displays may be viewed as environments themselves. In short, the stimuli must be viewed by the observer as an experiential world to afford an orientation-free representation. There are two distinct spatial representations being made; one more perceptual and episodic (orientation-free), and the other more integrated and model-like (orientation-specific).

Scholnick, Fein, and Campbell (1990) conducted an experiment to show that younger children (48-63 mos.) and older children (64-79 mos.) navigate with maps differently and that this difference can be used to predict their wayfinding performance. Younger children use landmark coding which provides static images of places. They do not chain them together into an array describing a path. They also rotate single elements of an array allowing for recognition from more than one perspective but are unable to “chunk” larger pieces of space into groups. They rely on direct perceptual information while traveling, minimizing the effectiveness and significance of the map. Older children integrate map information into a pattern of turns connecting landmarks. They rotate large clusters of an array enabling a more hierarchical spatial representation. They depend more on memory representations of space rather than on direct perceptual information. So older children perform some pre-navigation tasks to build a memory representation (i.e. a cognitive map) and to integrate map information allowing them to rely less on the map while navigating. The reverse is true for younger children. Blades and Spencer (1988) give further support for this idea showing that young children can use simple maps even if they are not aligned with the environment. However, they relied heavily on landmark information for navigation.

On the topic of landmark methods of wayfinding, Allen, Kirasic, Siegel, and Herman (1979) showed that adults and children may not select the same features as environmental landmarks. Children are less capable of selecting useful landmarks illustrating that the ability to use environmental landmarks developmentally precedes the ability to assess the potential value of a landmark.

Knowledge Accessibility

The main issue in this section concerns how spatial knowledge is retrieved for use on a wayfinding task once it has been acquired and integrated into a cognitive structure. Sholl (1987) states that if a cognitive map is an orienting schemata (Neisser, 1976), a prediction can be made that the cognitive map should have no preferred orientation and that targets in front of the body should be localized faster than targets behind the body. Cognitive maps are mental structures specialized to direct both perceptual and motor exploration of the environment. This gives special status to things in front of the viewer since they are perceptible stimuli. Furthermore, there should be no alignment problem since an orienting schemata *is* the person's perspective of the environment. As discussed in the previous section, knowledge acquired from maps is encoded in an orientation-specific form. However, this can be explained in terms of the processes involved (Rieser, 1983). Sholl is concerned with what Reiser refers to as perceptual (automatic) processes while any study using maps involves deliberate, cognitive processes.

The model of spatial representation Sholl identified was later investigated by Bryant, Tversky, and Franklin (1992; Franklin & Tversky, 1990). Their experiments show support for the spatial framework model of spatial representation. The spatial framework model states that the accessibility of objects depends on their direction along three differentially accessible axes defined by the body orientation (egocentric frame of reference). Objects in front are accessed most easily. This is in contrast to the equiavailability model which says objects are equally accessible in all directions. While this oversimplifies the issue, the mental transformation model offers a more complex solution stating that objects in front are easiest to access with all other objects being a function of their angular disparity with the front.

The preceding sections have surveyed the experimental psychology literature on cognitive map theory. The conclusions drawn from this body of research will be used as the basis for describing an environmental design methodology such as urban planning and architectural design (See Environmental Design on page 57.) or for wayfinding in virtual worlds. The following section will describe hypermedia navigation and its relationship to spatial wayfinding. The chapter concludes with anthropological examples of navigation and wayfinding in order to show concrete examples of how spatial knowledge is acquired and used in real world situations vastly different from those of the typical urban dweller.

Navigating in Hypermedia

An analogy could be drawn between navigating virtual spaces and navigating hypermedia since the problem of disorientation in hypertext and hypermedia is well documented (McKnight, Dillon & Richardson, 1991; Nielsen, 1990). Users of hypermedia systems seem to suffer from the same lack of structure in navigation as real and virtual world navigators. Hypermedia has clearly defined *paths* from one point to another. A path from one point to another is described in terms of the sequence of links which connect them. Users commonly become entangled in these links and are unable to discern how to find a specific page or information item. This discussion will begin with a look at navigating a linear form of hypermedia; a book. From there, navigation problems associated with hypertext and hypermedia will be examined and compared to navigating real and virtual spaces.

Nielsen (1990) notes that navigating a book is conceptually different from navigating space. There is no need for procedural or survey knowledge. A book is linear providing one and only one path between any two points. The only concrete similarity between navigating a book and navigating a space is in the use of landmarks. Readers often use bookmarks or “dog-ear” pages to mark pages of interest. Significant problems begin to occur only when the structure of the media is nonlinear as is the case with hypermedia.

As users become familiar with a hypermedia system, they begin to develop a form of procedural and survey knowledge. The “pages” of the system are viewed conceptually as nodes in a graph. As the graph is traversed repeatedly, the user’s mental representation of it becomes connected and tends toward completeness (See Spatial Knowledge on page 22.). However, McKnight (1991) notes that the evidence is far too weak to conclude that this knowledge is conceptually identical to spatial knowledge. Hypertext browsers and maps are different from spatial maps. They lack the directional information inherent to a spatial representation (i.e. north, south, east, west) while containing only up and down information relative to the hierarchy of nodes. This introduces an ambiguity to survey knowledge developed from such a space. Consequently, hypermedia developers often make use of the spatial metaphor to disambiguate this representation. Accordingly, the most common metaphor for hypermedia navigation is that of travel (Nielsen, 1990).

Real World Wayfinding

History has shown that the necessity to orient with the environment to enable purposeful motion has guided different cultures in the development of wayfinding techniques. As humans go about exploring their habitat, a need arises for methods which will be effective in that environment whether it be land, sea, or air. While the objective of all wayfinding techniques remains constant, it is interesting to note how vastly different the solutions have been.

Contemporary environmental wayfinding problems occur everywhere. Trailblazing can be thought of as two-dimensional† navigation in an environment typically rich in cues useful in orientation and navigation. Marine navigation, on the other hand, is two-dimensional navigation in an environment void of useful cues by which to navigate. Aerial navi-

† We use the term two-dimensional to denote navigation on the ground versus three-dimensional navigation which can be thought of as aerial navigation or two-dimensional navigation plus altitude. A more thorough definition will be presented in Spatial Characteristics on page 90 in reference to navigating virtual worlds.

gation is clearly three-dimensional navigation which may have access to environmental cues if flying over land in clear weather or may be lacking those cues if the ceiling is low or the flight is over the sea.

Anthropological Studies

The first indication of wayfinding assistance in any culture is their use of language to describe places, directions, and distances. As we would expect, the density of place names increases with proximity to home. However, in some cases the density can be astounding. On Tikopia island, there is a small sacred cleared space in the forest used for annual rituals for which the language has over twenty named locations (Firth, 1936). Similar examples can be found in other societies in Iran and Tibet, to name a few. The Aleuts give no names to large environmental features such as mountain ranges and peaks but they painstakingly have given names to the smallest of waterways; presumably because this is their primary mode of travel (Geoghegan, 1944). The Arunta of Australia divide their territory into sections which are connected by paths with wasteland in the areas between (Pink, 1936). There is normally only one correct path from one place to another. In imperial Rome, the city was addressed by districts rather than house numbers. The assumption made was that if you could find the district of the desired destination, you could find it within the district by personal inquiry. Similarly, James Michener writes

> Texas, unlike any other state, wrote its history in relationship to its counties. This was partly because the state was so enormous that it had to be broken down into manageable regions, but more because the towns within the regions were often so small and relatively unimportant that few people could locate them. A man or family did not come from some trivial county seat containing only sixty persons; that man or family came from an entire county, and once the name of that county was voiced, every knowing listener knew what kind of man he was. ... One either knew the basic counties or remained ignorant of Texas history. (Michener, 1985) p. 943

It could be argued that this tends to make a Texan's view of the world a bit distorted (See Figure 3-7), but in fact we know that distortion occurs in all mental representations of space (See Knowledge Representation on page 27). These are examples of how a society or culture will explicitly divide a large space into smaller ones for the purposes of simplifying wayfinding and spatial knowledge acquisition.

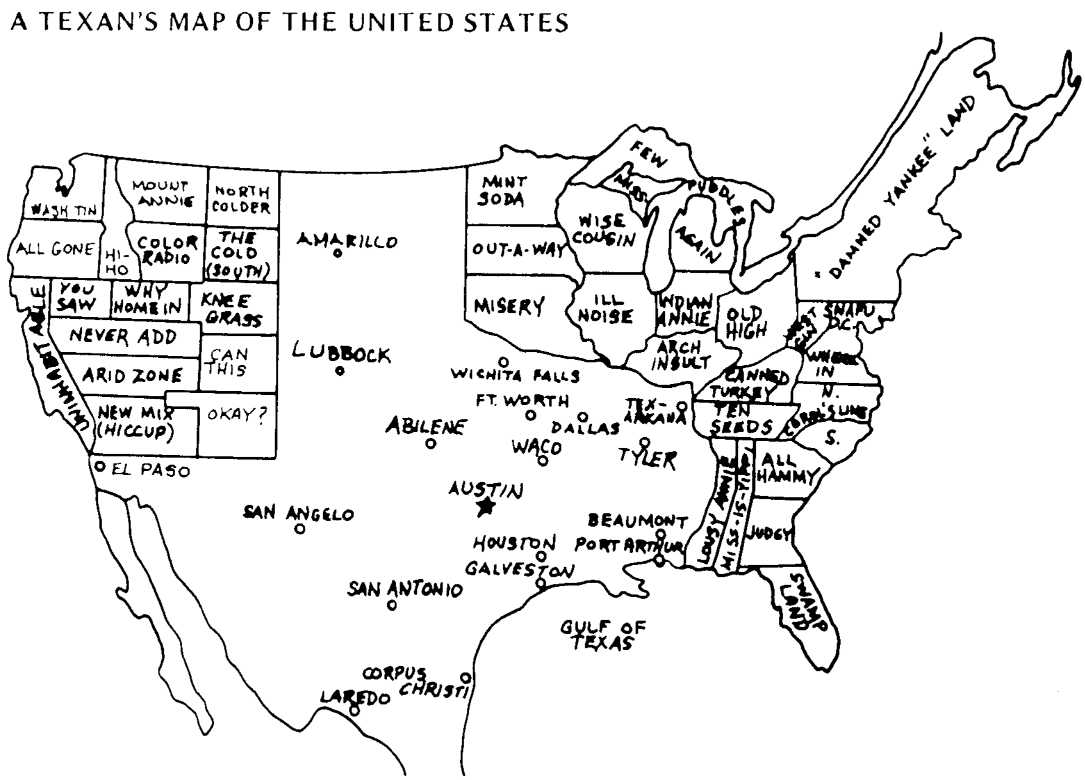

Figure 3-7 A humorous representation of spatial distortion. Reproduced from (Downs & Stea, 1977).

The Chukchee people of Siberia have a complex system of compass points. Their system is three-dimensional and directly related to the sun. They define 22 distinct directions. The system used in the North China plain was first developed for use in orienting buildings and other permanent structures (Winfield, 1948). The people find it so effective that they now give directions by the system rather than by left or right, as we do. The interesting fact here is that this system is exocentric† rather than egocentric in nature. Exocentric systems are fixed in space outside the person and thus universal requiring no translation from person to person.

† I use the term "exocentric" in keeping with the terminology of the author. However, the reader should note that "exocentric" and "geocentric" frames of reference are identical. They are fixed in the environment and are external to the observer.

To indicate direction, since the island of Tikopia is rather small, the natives use the words *inland* or *seaward.* These terms are used so commonly, Firth (1936) reports overhearing one native tell another “There is a spot of mud on your seaward cheek.” The Arunta have made a habit of always referring to an object in terms of its proximity, orientation, and visibility to the speaker. This typically simplifies the task of listeners to translate the location of the object from the speaker’s frame of reference to their own. For the Eskimo, direction can be related in terms of prevailing winds or by the drifts of snow which are a product of those winds. This method is used in lieu of celestial navigation which is typically secondary.

Many people from so called primitive cultures have acquired a highly developed skill in landmarking and wayfinding. Several seafaring cultures, particularly Arctic and South Sea peoples, have noted that under certain conditions, clouds reflect a map of the earth below. Open sea reflects white, while land reflects a darker grey. This is used to locate landmarks below the horizon. As efficient as these navigators may seem to be, there are certain artifacts which they routinely overlook. The Aleuts, for example, do not recognize that the islands they call home form an obvious chain. This is particularly amazing considering that the Eskimo are able to construct detailed maps covering hundreds of miles (including the Aleutian islands). The Puluwatan navigators can correctly identify, name, and give the relative positions of all the islands of the archipelago. This is no simple task considering the archipelago is 1500 miles long. The early mountaineers who first travelled over this country and later paved the way for settlers to follow, used landmarks to guide them as well. These were typically founded on markings related to travel such as rivers, streams, and mountain passes. However, they also used landmarks of danger areas or impassable areas such as mountain peaks and waterfalls.

One of the most well documented and compelling examples of primitive navigation strategies is that of the Puluwatan navigators of Puluwat Island in the Pacific Ocean near the Caroline Islands (Gladwin, 1970; Neisser, 1976). Their skills as navigators are quite diversified. They are able to pick up seemingly imperceptible bits of information. A slight water color change indicates a reef. The rhythm of the waves slapping against the side of the boat indicates a particular crossing wave pattern. The direction of flight of a flock of birds indicates the probable direction to a nearby island (See Spatial Knowledge on page 22.). Aside from their remarkable ability to extract subtle cues from their environment are their highly advanced cognitive abilities. Their mental representation of their environment is based on a conceptual structure called the *etak*. Basic directions are defined in terms of the place on the horizon where familiar stars rise. There is a known star course to take between any two islands. However, more often than not, there is no direct star course to take from one island to another. Furthermore, star headings are unreliable since they can only be seen during the day or on clear nights.

The etak system places islands (and sometimes "virtual" islands) in known positions relative to the star bearings. As a navigator proceeds along a journey, he uses a nearby island (which most often is over the horizon and out of sight) as a reference. As the journey proceeds, the reference island will move from one bearing to another. In the example in Figure 3-8, at the point of departure, the reference island lines up with Gamma Aquilae. It will change bearings until, at the destination, it is aligned with the Little Dipper. Each segment of the journey, defined as the distance from one star heading to another, is called an etak. They are not of a uniform length. In fact, although this is their method of determining distance, this does not mesh with their conceptual model of what is happening. Since, from their perspective, the reference island changes bearing by slowly moving backward, it is the island rather than themselves which is moving. The point here is that the navigators simplify their highly complex environment to accomplish their task.

Trailblazing

Traditionally, trailblazing was (as the name implies) the creation of a path or route through unknown territory. It was largely a matter of accurate landmarking over a large region of wilderness. Today, trailblazing is typically done with a compass and a topographical map. Maps for use in trailblazing are usually color-coded with man-made artifacts in black and natural artifacts in color (See Figure 3-9). Contour lines are used to

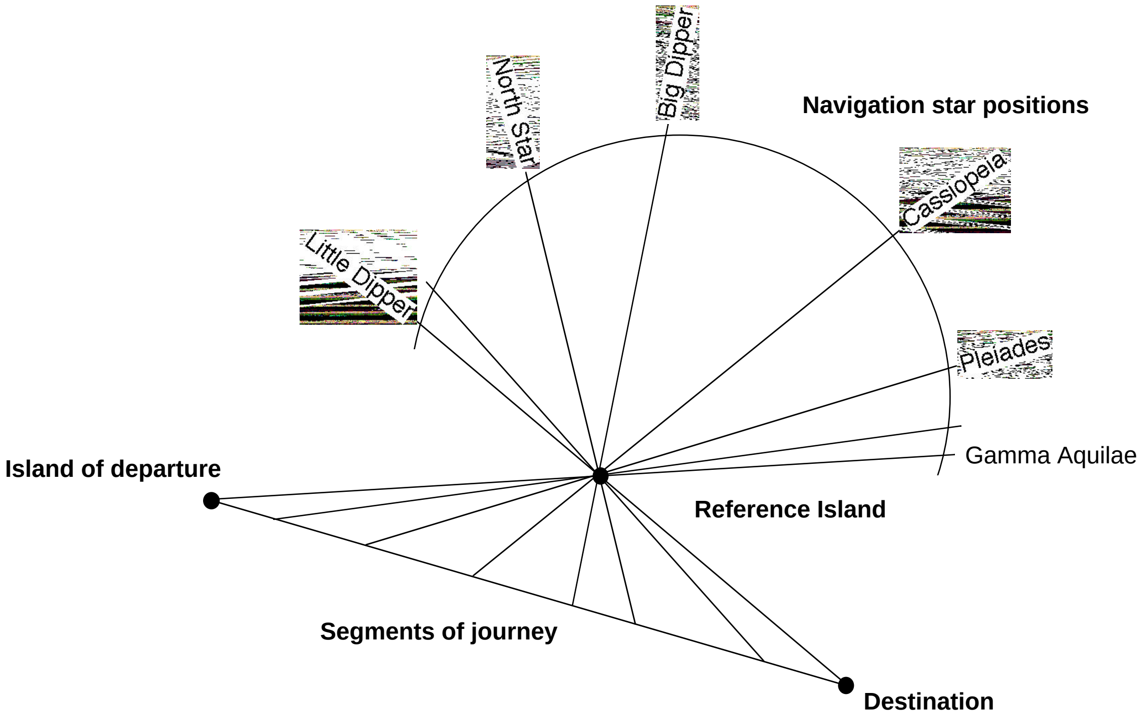

Figure 3-8 The ETAK system. Reproduced from Gladwin (1970).

represent terrain elevation. However, they do not explicitly note areas unsuitable for foot travel. The trailblazer will use a compass to mark the bearings of selected landmarks. In fact, the foremost task of the trailblazer is to identify appropriate landmarks which can be followed by other travelers. This is not necessarily an easy task. Consider the case of travel over desert terrain or through dense woods. The trailblazer will most likely have a difficult time locating landmarks which can be followed.

An important point to make concerning trailblazing is that the "trail" consists of a sequence of landmarks to be followed in order to reach some desired goal location. The actual path between the landmarks is not necessarily clear. Therefore, a straight line between two successive landmarks may lead across a lake. It is the obligation of the traveler to either cross the lake or walk around it to pick up the bearing to the next landmark on the other side (Boy Scouts of America, 1967).

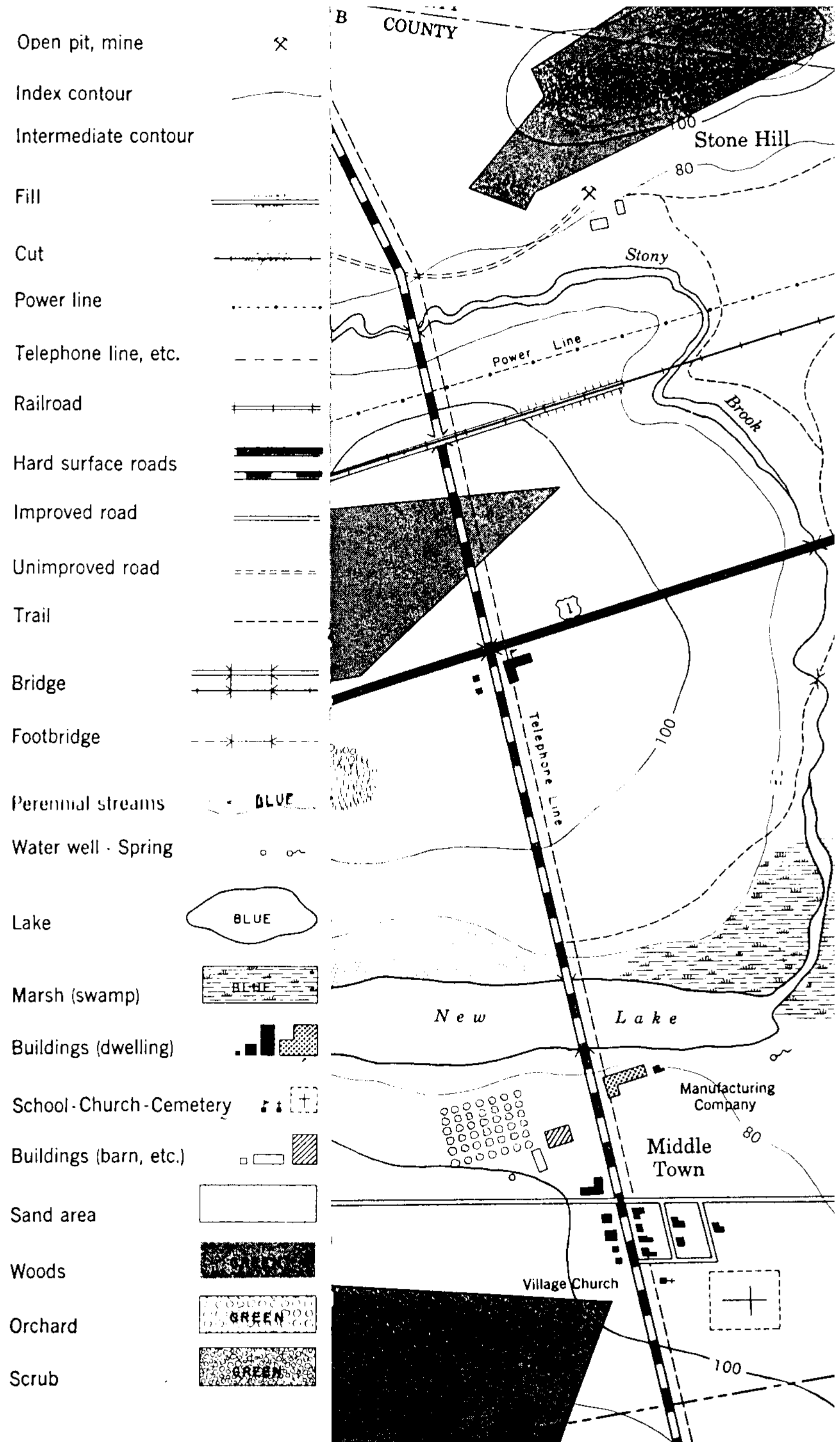

Figure 3-9 A typical trailblazing map with contour lines. Reproduced from Boy Scouts of America (1967).

Marine Navigation

Marine navigation is defined as the science of conducting a ship from port to port and determining her position on the surface of the sea at any time during the voyage. It is divided into five primary parts.

1. *Pilotage* is used when navigating by landmarks. This is considerably easier than open sea navigation but the consequences of an error could mean running the ship aground. Accuracy is crucial. If natural landmarks are lacking, artificial landmarks such as buoys, lighthouses, lightships, foghorns, and submarine bells may be used. Finely detailed charts have been produced which show all danger areas, key visual landmarks (mountains, trees, ports, etc.), and tidal information (Hill, Utegaard, & Riordan, 1958; Waters, 1958; Waters, 1967). But beyond visual contact with the coast, this information is useless.
2. *Dead reckoning* is used when on open seas. This is more difficult than pilotage but greater inaccuracies are allowed typically without significant consequence. The navigator tracks speed,[†] distance, and direction. As deviation from the desired course increases from errors, celestial navigation may be used to make corrections. Dead reckoning derives its name from its original title, *deduced reckoning.*
3. *Celestial navigation* is the science of accurately determining a geographical position at sea by observing celestial bodies and fixing the observer's position on the Earth's surface with respect to them. This technique requires the use of a chronometer (high-precision clock), a sextant (measures vertical angles relative to the horizon), a nautical almanac (notes the positions of stars and planets on any day of the year), and math tables (trigonometric tables to compute the exact position of the ship given the time and astronomical data).
4. *Directional radio* is an aid to navigation in establishing the bearing of shore stations and is sometimes considered a part of pilotage. On board the ship, an instrument called

† The term "knot" comes from an early system for speed determination. A log was tied to a knotted rope and tossed overboard as an hour glass was turned. When time expired, the speed was noted as the number of knots which had passed over the side of the ship. Today, one knot equals one nautical mile per hour.

the radio direction finder (RDF) homes in on the signal displaying the direction and distance to that beacon.

5. *Global positioning system (GPS)* is a recent development to navigation in general. It is an automatic method of determining the latitude and longitude of the current position using signals received from satellites. This method is very accurate but has not typically been used in very small craft until recently.

There is a tendency to confuse pilotage with dead reckoning. Dead reckoning is a method by which the position of the craft can be determined at any time along a track by knowing the direction and speed at which the craft is moving. Pilotage is a method by which the position of the craft can be determined by recognizing landmarks and the craft's position relative to them. Dead reckoning is used both when the shore is visible and when it is not. In the first case, position can be determined from dead reckoning alone but pilotage or astronomical navigation can assist the pilot in eliminating error. In the second case, pilotage cannot be used and error must be corrected through celestial (or some other) navigation.

In summary, marine navigation techniques explicitly maintain orientation through the use of mechanical devices. Wayfinding is typically done through the use of maps on the open seas or through landmark knowledge close to shore.

Aerial Navigation

Aerial navigation is defined as the science of conducting an aircraft from place to place upon the Earth and in establishing its position in relation to the Earth's surface. It is sometimes referred to as *avigation*. Aerial navigation is largely a transfer of knowledge from marine navigation to the air. The same concepts (the five subdivisions described above) apply. However, to an aviator, navigation is more of an urgent issue due to the speed and mode of travel. Pilots can't stop and ask directions.

The earliest form of aerial navigation was done by balloonists. Through their experiences, ideas for aviation charts first appeared and the sextant was adapted for aerial use.[†]

Early in the 20th century, devices for measuring windspeed, heading, and altitude were developed. An early landmark system was created specifically for overcast and night flying. Bonfires were built by farmers and ranchers at predetermined times. Pilots would fly from bonfire to bonfire across the country. These were later replaced by light beacons. In 1926, these beacons covered approximately 2,000 miles; by 1929 they covered 10,000 miles, indicating the increase in air traffic. This type of landmark scheme was essential to making the airplane a useful and safe transportation tool (Holland, 1931; Wright, 1972).

The earliest aviation charts date to 1907. These charts had color-coded contour lines showing elevation and symbols showing landing areas, obstructions, lines of magnetic variation, and key landmarks such as lighthouses and beacons.

Early solo pilots could only devote part of their time to navigation. They typically studied maps of the planned flight route before takeoff, memorizing key elements and sequences of landmarks. This method proved faulty. A World War I pilot once flew over a large city which he failed to recognize as Brussels. Although most pilots at the close of World War I continued to rely almost exclusively on landmark navigation, they were beginning to make use of information from minor cues such as smoke and wind direction in order to return from their missions successfully.

On his historic transatlantic solo flight on May 20, 1927 from New York to Paris, Charles Lindbergh first contacted land over Ireland two hours ahead of schedule and only three miles off target. This is an amazing fact considering that he often flew at altitudes as low as 50 feet above the ocean surface and used only dead reckoning along the way. This eliminated the possibility of any landmark navigation as he approached the shore. He commended the performance of his compass for this accuracy (Lindbergh, 1953).

However, as successful as Lindbergh was, other examples show that the technology and the methods were immature. Amelia Earhardt was lost at sea on July 5, 1937 presum-

† The adaptation mentioned was the “bubble” sextant (later perfected during World War I) which places a bubble, not unlike that in a modern carpenter’s level, on the sextant to create a virtual horizon which is level with the line of flight.

ably from a navigation error which caused both her and her navigator to miss Howland Island on the equator north of Samoa (Rich, 1989).

Because useful visual landmarks were often scarce, many aviators proposed the use of elaborate guides to assist in navigation. These were thought to be analogous to street signs or highway markings. One suggestion proposed visibly dividing the countryside into sections with lines. However, air traffic volume could not warrant the use of such drastic measures.

The late 1940's saw the development of Very High Frequency Omni Directional Range (VOR) technology. This is the predominant form of radio navigation in use today. A VOR station transmits beams called radials outward in every direction. The receiver detects the signal and determines what radial the aircraft is on. The VOR gives the airplane's position to (or from) the station based on magnetic north. The needle on the display represents relative position of the station to the aircraft (See Figure 3-10.). If the needle is to the left of center, then the station is to the left of the aircraft (Kershner, 1960; 1977) and vice versa.

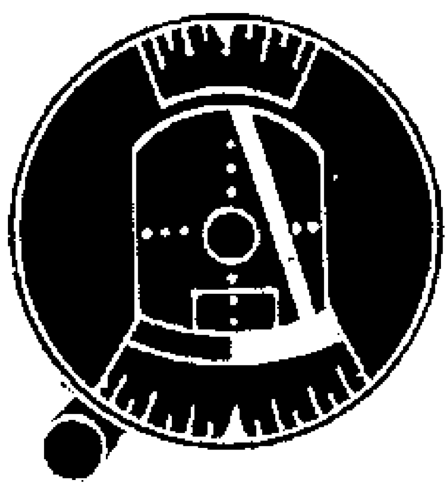

Figure 3-10 A VOR display. Reproduced from Kershner (1960).

The automatic direction finder (ADF) is a 0-360 degree radial dial with a pointer indicating the absolute direction to a radio beacon. The display gives essentially the same information as the VOR display without distance. (i.e. It gives a vector with no magnitude.)

The method of aerial navigation most applicable to virtual worlds is that of pilotage and landmark navigation. In actual practice, this is done by charting a flight path from airport to airport and noting landmark checkpoints along the way. An example flight follows (Kershner, 1960).

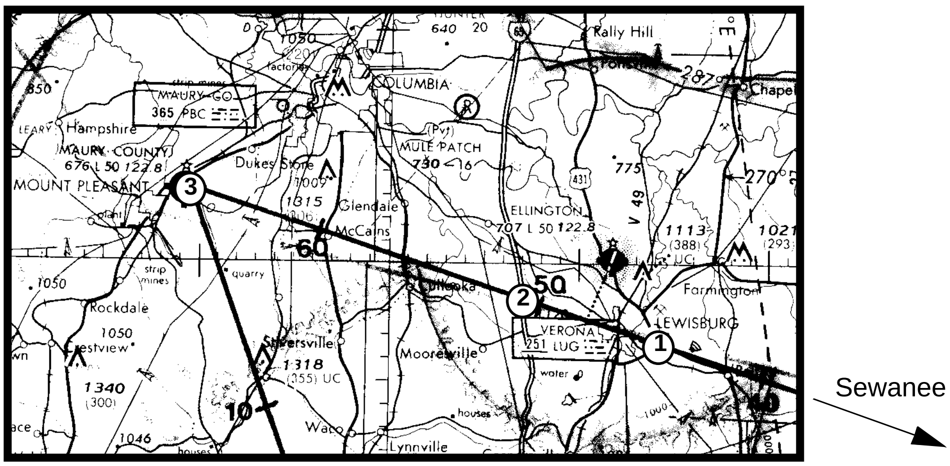

Figure 3-11 A sectional chart showing the flight from Sewanee to Maury County. The checkpoints are marked as circled numbers. Reproduced from Kershner (1960).

The chart (See Figure 3-11) shows the approach path from Sewanee to Maury County. As the flight nears its destination, it passes a number of specified landmarks (See Figure 3-12). The first checkpoint passes directly over Lewisburg. Shortly thereafter, interstate I-65 is crossed. And finally, Maury County airport comes into view.

From this example, we note that aviators use visible landmarks such as roads, towns, rivers, lakes, and quarries to navigate. As their altitude changes, so also will the types of possible landmarks. At low altitudes, a country road might be useful. But at several thousand feet, the same road would be difficult to detect. Therefore, other landmarks such as larger towns or lakes must be used.

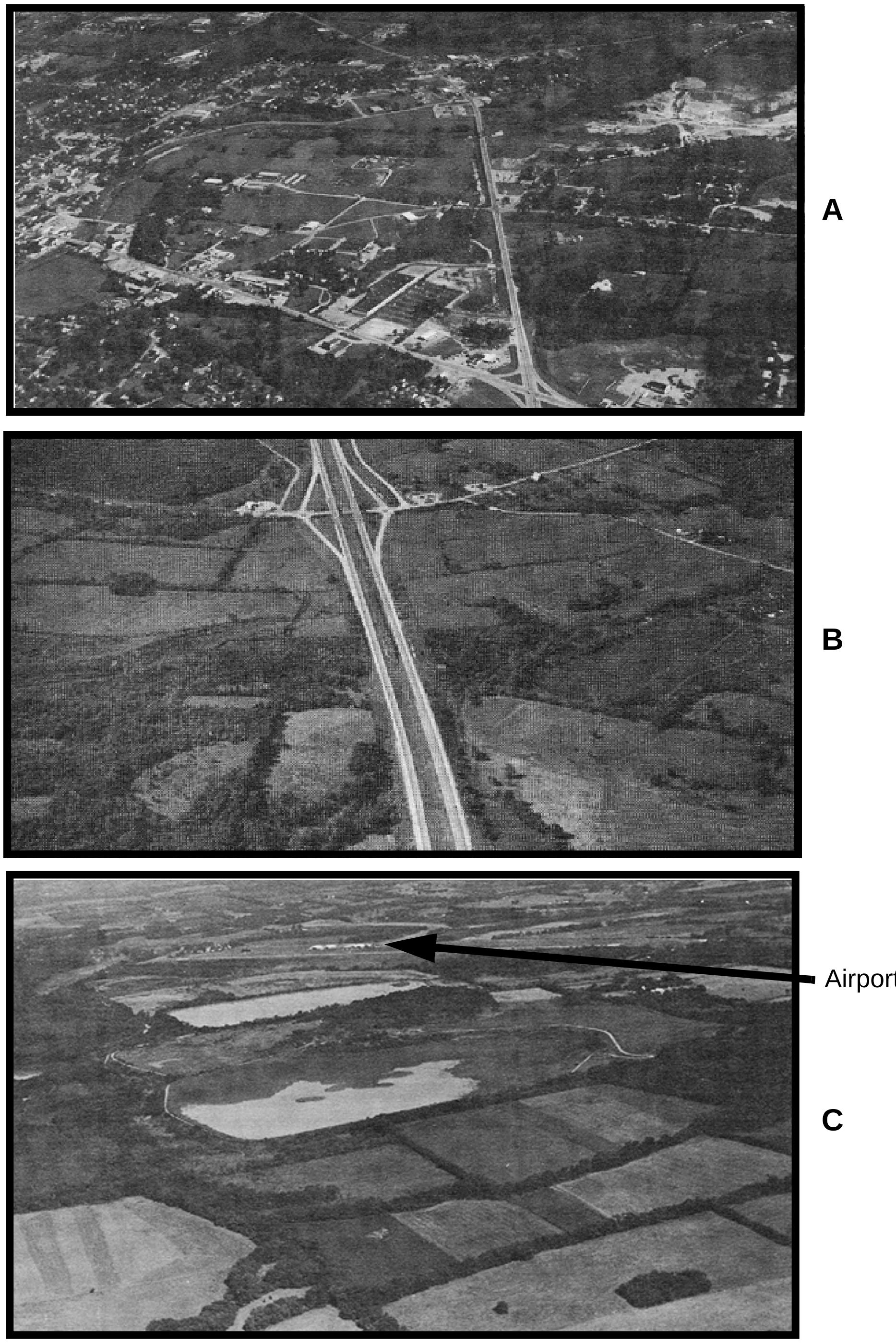

Figure 3-12 Aerial navigation landmarks. A) Checkpoint 1: The town of Lewisburg is below. B) Checkpoint 2: Interstate I-65 is below. C) Checkpoint 3: The Maury County Airport is just ahead. Reproduced from Kershner (1960).

Summary

The experimental studies described earlier in this chapter lead to two general conclusions concerning the representation of spatial knowledge.

1. Spatial knowledge is hierarchical. As such, an observer will tend to chunk space into large, logical units until it is more manageable. This is very similar to the concept described in Card, Moran, and Newell (1983) and Buxton (1986) as applied to human-computer dialogues.
2. Simplifications tend to be made to complex spatial problems. This is suggested by the taxi drivers' generalization of non-right angle blocks into rectangles. A true representation would be difficult to manage and to make inferences from. Therefore, a simplification was made.

Furthermore, we know that learning from direct experiential interaction with an environment tends to produce a more orientation-independent representation than learning from a secondary source such as a map. However, experiential learning takes longer to develop survey knowledge than map learning.

Lastly, human spatial orientation has two fundamental components; one being cognitive and deliberate while the other is perceptual and automatic. As the wayfinder's knowledge of a space increases, wayfinding tasks tend toward perceptual processes. Very little deliberate problem solving takes place. We will refer back to these items as part of the basis for wayfinding design principles.